FILE COPY
NO. 1-W

N 62 57649

TECHNICAL MEMORANDUMS

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 649

LIQUID COOLING OF AIRCRAFT ENGINES

By Hanns Weidinger

Zeitschrift für Flugtechnik und Motorluftschiffahrt
Vol. 22, No. 18, Sept. 28, 1931
Verlag von R. Oldenbourg, München und Berlin

FILE COPY
To be returned to
the files of the National
Advisory Committee
for Aeronautics
Washington, D. C.

Washington
December, 1931

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL MEMORANDUM NO. 649

LIQUID COOLING OF AIRCRAFT ENGINES*

By Hanns Weidinger

Introduction

The construction of aircraft engines is now limited to two highly developed types of carburetor engines, water-cooled engines with the cylinders in rows and air-cooled radial engines, both of which seem to have reached their extreme limits of development. The rivalry regarding the advantages of water-cooled engines as compared with air-cooled engines is still the same as at the beginning of their development, and the solution of the problem seems to be no nearer.

The problem of aircraft-engine cooling is inseparably involved with the demand for the minimum air resistance. While, for this reason, endeavors are being made to reduce the frontal resistance of air-cooled radial engines by streamlined cowlings and suitable conduction of the cooling air, and by the use of good-conducting cylinder heads forged in one piece from high-tensile light metal into the best form for heat conduction, to extend the field of air-cooled engines, the use of cooling liquids with high boiling points and low freezing points has given liquid-cooled engines a corresponding impetus.

In liquid cooling it is easy to prevent local overheating and to obtain any desired temperature in the cylinder jackets, providing the cooling plant is suitably designed. Moreover, the engine temperature can be kept under good control, since all heat disturbances are manifested by changes in the temperature of the cooling liquid. The great superiority of the liquid-cooled engine in heat receptivity results in a more uniform temperature. Since

*"Versuche mit Heisskühlung am Flugmotor." Abstract of a lecture before the W.G.L. (Wissenschaftliche Gesellschaft für Luftfahrt) at Kiel in 1931. Zeitschrift für Flugtechnik und Motorluftschiffahrt, Sept. 28, 1931, pp. 541-6.

the air-cooled engine must lose more energy in cooling in order to avoid local overheating, the water-cooled engine is somewhat more economical. This is demonstrated by the smaller fuel and oil consumption of the latter.

In order to retain the advantages of water cooling with a minimum cooling surface and thus approach air cooling, attempts have been made to use other liquids for cooling aircraft engines.

Especially on seaplanes, due to the long water run, the radiators are generally too small for high summer temperatures. As compared with landplanes, the flotation gear requires more power, and the requisite radiator dimensions offer such a high air resistance that the taxying, climbing and flight characteristics are appreciably impaired. If, however, a reduction in the size of the radiator would be advantageous for seaplanes, it would also be advantageous for landplanes.

Reason and Object of the Tests

It is, of course, obvious why we at the Travemünde seaplane testing station, impelled by the cooling difficulties of our large flying boats in midsummer, were the first to try other cooling liquids than water on aircraft. At our suggestion preliminary tests were made at the Munich Polytechnic School under the direction of Dr. Nusselt with the favorable result that, with increasing temperature of the cooling water, there was a considerable reduction in the quantity of heat abstracted by the cooling water. The tests were made with water, which was subjected to pressure for the purpose of raising the boiling point, on a six-cylinder BMW IV aircraft engine. The results were reported by Dr. E. Hecker in the V.D.I. (Zeitschrift des Vereines deutscher Ingenieure) of April 12, 1930.

This method of cooling could not be employed directly, because any lack of tightness of the radiator would allow the water to evaporate. Moreover, the obstruction to the circulation of the water would constitute an unjustifiable impairment of the safety factor.

The use of evaporative cooling would have necessitated great modifications in the airplane and power plant. Hence attempts were first made to do the cooling with some liquid

physically similar to water, but with a higher boiling point. Since water, aside from its low boiling point and high freezing point, has all the advantages for cooling, some disadvantages must be accepted in using other liquids.

The tests at Travemünde were made with the same BMW IV engine as at Munich with three liquids, namely, ethylene glycol ($C_2H_6O_2$), coolant 82 (I. G. Farben) and a transformer oil (Rhenania Ossag Company). The boiling point of all these liquids is higher than the maximum cooling temperatures the engine can stand. Comparative tests were first made with water and the three above-mentioned liquids on the test-stand in Travemünde, the object of which was to determine whether the engine functioned perfectly at the high temperatures; whether an endurance run was possible and how the horsepower and fuel consumption were affected. The correctness of the test-stand results was then to be tested practically with the same engine on an airplane. A further object was to determine the maximum attainable cooling temperatures. Since the more important thermal relations had already been investigated in Munich, and since a thorough investigation by the D.V.L. (Deutsche Versuchsanstalt für Luftfahrt) was nearly finished at the time, the following tests were made from a purely practical standpoint.

As had been expected, it was found that the normal piston clearance of 0.4 to 0.6 mm (0.016 to 0.024 in.) no longer sufficed. Beginning at the head, each piston was turned off conically to about 1.2 to 0.6 mm (0.047 to 0.024 in.) clearance. Likewise the gap in the piston rings was increased by 0.1 mm (0.004 in.). These measures proved very successful. During the whole course of the tests, there was no seizing of the pistons, no increase in the oil consumption was manifest, and the power remained uniform. Moreover, special rubber gaskets for high temperatures, made by the Heede Company in Hannover, were used between the cylinders. These proved very satisfactory after preliminary tests had shown that the ordinary rubber gaskets were not damaged by glycol but by the high temperatures.

The Cooling Liquids Used

The essential characteristic of a cooling medium is that it should have a definite minimum boiling point of

not less than 180°C (356°F.). It is also important that the cooling liquid should have no corrosive action, should not attack rubber, should physically resemble water and should not be inflammable. No liquid has yet been discovered which fulfills all these requirements. The best ones seem to be glycol and coolant 82. Glycol, which has been successfully used in American experiments under the name of "Prestone," is an organic liquid which, aside from its low flash point of 116°C (240.8°F.), approximately fulfills all the requirements. G. W. Frank reports, in the 1929 S.A.E. Journal, successful endurance tests made with "Prestone" by the American Army and Navy both on the test-stand and in flight in 1923-1926. It has a high boiling point of 197°C (386.6°F.) and a very low freezing point of -37°C (-34.6°F.), so that it is an excellent protection against freezing. Glycol can be mixed with water in any proportion. Unfortunately, however, the boiling point falls very rapidly with the freezing point. It is a great disadvantage therefore that the liquid is hygroscopic. With the absorption of 10% of water, the boiling point drops to 140°C (284°F.), while the flash point rises to 130°C (266°F.). This disadvantage can be largely overcome, however, by the exercise of sufficient care. With the same glycol we flew 42 hours over a period of 11 weeks without the boiling point falling below 160°C (320°F.), which indicates a water content of not over 4%.

The second cooling liquid, coolant 82 of the I.G. Farbenindustrie, seems to be almost identical with glycol. At any rate, the physical properties of the two liquids are almost the same.

The third cooling liquid was a transformer oil produced by the Rhenania Ossag Company. The boiling point of this oil is above 200°C (392°F.), but does not seem to be very definite. We had to discontinue the tests with this oil, because easily boiling constituents did not allow a higher temperature than 140°C (284°F.). Its flash point is not much higher than that of glycol. The chief objection to the use of this oil as a cooling medium is the fact that it is almost impossible to insure tightness of the cooling plant with rubber gaskets.

In Figure 1, the specific gravities of the three liquids are plotted against the temperature.

The specific heats, which are necessary for calculating the amount of heat absorbed by the cooling liquid, are

plotted against the temperature in Figure 2. These naturally vary with the amount of water absorbed by the liquids. There are no reliable data for the rather low specific heats of the transformer oil.

Test-Stand Experiments

The engine was mounted on a sound-damping test-stand in Travemünde. The engine bed with the engine was installed in the tunnel-shaped chamber, while the observation chamber was separated from it by a concrete wall. Figure 3 shows the engine mounted on the pendulum frame. The air drawn in by the propeller came through the wooden tunnel shown in the foreground, which was connected with an air shaft 14 m (46 ft.) high. The air flowed right and left past the engine and left the test chamber through an expanding vertical shaft. The engine was cooled by two large airplane radiators on opposite sides of the propeller slipstream. The mean temperature of the cooling liquid was raised by wrapping the radiators with strips of linen.

Figure 4 is an accurate diagram of the whole arrangement. The circulation of the cooling liquid was maintained by an engine-driven pump and remained nearly uniform, as the r.p.m. of the engine was not changed during the tests. The quantity of the circulating liquid was determined by an I.G. measuring orifice installed in the conducting pipe. Moreover, an expansion tank, open at the top, was connected with the pipe, so that the liquid was always under atmospheric pressure.

A series of tests was first made with water as the cooling medium for comparison with the other liquids. All the tests were made at full load. The quantity of heat absorbed by the cooling medium was calculated from the hourly quantity of liquid, the increase in temperature of the liquid between inlet and outlet, and the specific heats.

In Figure 5 the heat absorbed by the liquid is plotted against its mean temperature. It is about 7% higher than in the Munich tests. This difference is due to the difference in the test equipment and to the greater hourly quantity of liquid in the present tests. The chief result is that, at about 140°C (284°F.) mean temperature of the liq-

uid, only half the heat is absorbed, as compared with a temperature of 50°C (122°F.), due to the smaller temperature difference between the gas and the cooling liquid and to the higher surface temperature of the engine and the consequent increase in heat radiation.

In Figure 6 the heat absorbed by the liquid per horsepower per hour is plotted against the mean temperature of the liquid. The scattering of the test points is much greater with glycol than with water. This is ascribable to the fact that the calculations of the points are unreliable, due to the changes in the specific heat and specific gravity resulting from the absorption of water by the glycol during the tests. Moreover, since the viscosity of glycol is greatly affected by the temperature, the rate of flow of the liquid varies, especially at lower temperatures. This fact is likewise confirmed by the course of the two curves.

In practice the most important result is that the use of glycol causes no thermal shifts as compared with water. With the same effective radiating area, there is almost no difference in the mean temperature of water and glycol.

In Figure 7 the horsepower N_0 and the r.p.m. are plotted against the temperature of the cooling liquid. In spite of the considerable scattering, which is not strange with the inaccurate calculation of N_0 (the tests being made on several different days), the maximum power and revolution speed were attained at a mean temperature of the cooling liquid of about 100°C (212°F.). With a mean temperature of 140°C (284°F.) of the liquid, the power fell 3.5% as compared with that at 70°C (158°F.), which is small in view of the advantages in other respects. There was no perceptible change in power due to the use of glycol instead of water. Similar relations obtain in the specific fuel consumption, which is plotted against the mean temperature of the liquid in Figure 8.

Flight Tests

The choice of the first experimental airplane was determined by the fact that we wished to use the same engine and that the radiator consisted of several removable plates, so that its size could be reduced.

The experimental airplane Arado SCID 1241, which fulfilled these requirements, is shown in Figure 9. The BMW IV engine with normal compression, which was used in the stand tests, was installed after careful inspection. The ventilation was improved so as to remove any possibility of the glycol coming in contact with the hot engine. A large vertical sheet-metal screen was placed on the exhaust side, through which the six exhaust pipes led.

The radiator consisted of 19 plates of 0.575 m^2 each of effective area and was mounted under the fuselage. The liquid was kept in circulation by a standard pump. Reduction in the cooling area and the consequent increase in the temperature of the liquid was effected by removing individual plates. The temperature of the liquid, on entering and on leaving the engine, was measured by a steam-pressure thermometer made by Schafer and Budenborg of Magdeburg. All the principal test instruments were installed in the second cockpit, as shown in Figure 10: on the left, the two large-scale thermometers for the liquid temperatures; on the right, the thermometer for the temperature in the oil sump, the DVL tachometer for accurately indicating the engine r.p.m. and in the middle a threefold instrument for recording the dynamic pressure and the flight altitude.

The principal object of these experiments was to determine the reliability of liquid cooling in flight, the maximum cooling temperature, and to represent the results in numerical form. The first flight tests were made with 19 radiator plates. After a flight of 15 minutes, when it could be assumed that the engine was fully warmed up, an 8-minute horizontal flight was made near the ground with wide-open throttle. During this time the triple recorder was switched on, the engine r.p.m. was noted, and the temperatures of the inflowing and outflowing liquid, of the oil and of the outside air were recorded. The same test was made at three other revolution speeds. In flight at a constant r.p.m. the temperatures quickly became constant.

Further experiments were tried after removing two radiator plates at a time and finally one plate at a time. The smaller the number of plates, the higher the temperature of the liquid became, until the maximum limit was finally reached. For various reasons (including absorption of water by the glycol), 150°C (302°F.) should not be exceeded. This limit was reached with six plates at an

outside temperature of 11°C (51.8°F.). In a test with five plates, the temperature of the liquid rose to over 160°C (320°F.). This sudden great temperature rise indicated that the radiator plates nearest the fuselage contributed but little to the cooling. Presumably the flow resistance of the radiator had also increased considerably, since the temperature difference of the cooling fluid between the inflow and outflow was not less as compared with the stand tests. Two measures were therefore adopted. A better cooling of the radiator plates in the air flow was effected by leaving more space between them and the fuselage, and the amount of liquid flowing through them per unit of time was increased. As shown in Figure 11, the radiator plates were mounted farther from the fuselage, so that flights could be made with only five plates.

Altogether 70 flights with a total flying time of 42 hours were made within a period of nine weeks with glycol as the cooling medium. The measured cooling-liquid temperatures had to be reduced to a constant outside temperature, in order to be able to compare them with one another. Since the mean outside temperature during the tests was about 11°C (51.8°F.), all values were correspondingly converted on the assumption of a direct proportionality of the cooling-liquid temperature.

The effective radiator area, which could not be calculated from the test-stand data, could be here determined. The 19 plates, as used for water cooling, had an effective surface area of 10.93 m^2 (117.65 sq.ft.). This area was taken as the basis and the effective radiator area was expressed in per cent. We thus obtained the curves representing the effective radiator area in terms of the cooling-liquid temperature. (Fig. 12.) The middle curve, reduced to 11°C (51.8°F.) outside temperature, represents the effect of removing plates from the bottom. The drop is very steep. The gradual flattening of the curve is due to the ineffectiveness of the plates too near the fuselage. Improvement is possible by increasing the efficiency of the radiator by suitable methods. If the radiator is brought more into the wind, the left curve is obtained. Perhaps still better results can be obtained by giving the radiator, at the outset, the correct design for liquid cooling at high temperatures.

The most important test result is that, at 145°C (293°F.) mean temperature of the cooling liquid, only

26.3% of the original effective radiator area is required, i.e., a saving of 73.7% due to the increase of about 70°C (126°F.) in the temperature of the radiator surface. The requisite effective radiator area per horsepower is thus reduced from the original 0.04 to only 0.011 m^2/hp.

If the mean cooling-liquid temperatures are plotted against the engine revolution speeds, the fall of the curves from right to left represent the fall of the mean cooling-liquid temperatures due to throttling the engine. It is obvious from Figure 13 that a given throttling yields a greater temperature drop for high cooling temperatures than for low ones. This result is likewise important for designing radiators for liquid cooling at high temperatures. Figures 14 and 15 show a comparison of the original radiator with the smallest one.

During the test period, there was no falling off in the r.p.m., no seizing of the pistons, no valve leakage, nor other trouble. The rubber gaskets did not give out, and the spark plugs did not have to be replaced. Only the engine became more sensitive with regard to the fuel. The original 50-50 mixture of gasoline and benzol had to be replaced for high cooling temperatures by a mixture containing 80% of benzol. The "Aero H" oil of the German Vacuum Oil Company yielded good results. There was no greater oil consumption in flight, and the mean temperature was 65°C (149°F.), as in water cooling. Unfortunately, the breaking of an exhaust valve in the flight to Munich after the completion of the tests resulted in damage to the piston and engine housing. It could not be determined as to whether the break was caused by liquid cooling at high temperatures or by defective material. A careful inspection of the dismantled engine showed that the wear of all the parts was normal, and that the exhaust valves were not distorted.

Summary

It is sought to solve the problem of liquid cooling at high temperatures, which is an intermediate method between water and air cooling, by experiments on a test-stand and on an airplane.

A utilizable cooling medium was found in ethylene glycol, which has only one disadvantage, namely, that of com-

bustibility. The danger, however, is very slight. It has one decided advantage, that it simultaneously serves for protection against freezing. The absorption of water from the air might lower the boiling point so that the liquid would evaporate.

As regards the engine, no objection has thus far been found to liquid cooling at high temperatures. The loss in engine power is very small, provided the cooling temperature does not exceed 145°C (293°F.). This temperature was indeed found to be the best. The extended tests on the stand and in flight show that the engine can stand the increased thermal stresses, though it is possible that certain parts (e.g., exhaust valves) should be made from high-grade materials.

An important point is the reduction in the size of the radiator, which has always been difficult to install on an airplane. Our results admit a reduction of 70% in the original radiator area and probably even more. It may be assumed that this reduction will not only diminish the resistance of the radiator, but will make it possible to install it in an airplane in such a way as to eliminate its resistance altogether, thus considerably reducing the drag of the airplane.

The reduction in the size of the radiator will enable an increase in the speed of the airplane, which may be quite large on a very swift airplane. Moreover, there is a saving in weight, about 32 kg (70 lb.) in the present case, which is very desirable.

Increased attention must be given the radiator packing. It is still to be determined whether higher-grade fuel should be used in liquid cooling at high temperatures.

Further results of liquid cooling at high temperatures lead to the union of the radiator and engine by a special cylinder jacket and to an increase in the number of cooling fins on the engine housing. We have the small air resistance of "in-line" engines and can in any case, in contrast with air-cooled engines, avoid local overheating, since the cooling liquid removes the heat from any part to an almost unlimited degree.

In conclusion, I wish to express my thanks to my co-worker, Dr. L. Auer, for the performance of the experiments and the evaluation and arrangement of the results.

Translation by Dwight M. Miner,
National Advisory Committee
for Aeronautics.

a; Glycol

b, Transformer oil

c, Coolant 82

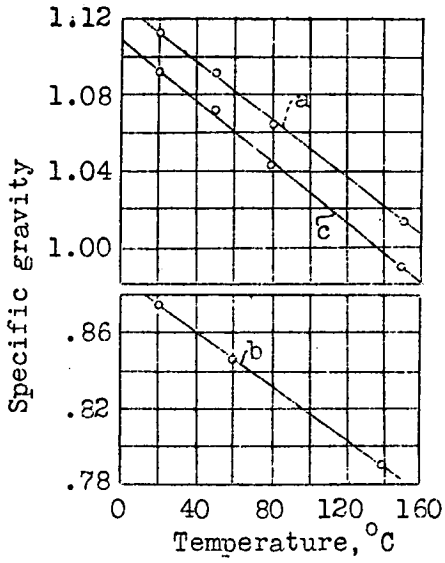


Fig.1 Specific gravity against temperature.

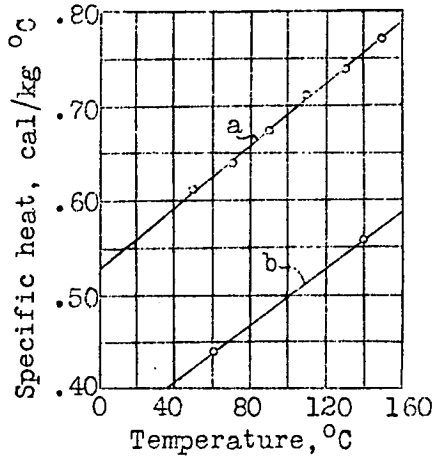


Fig.2 Specific heat against temperature.

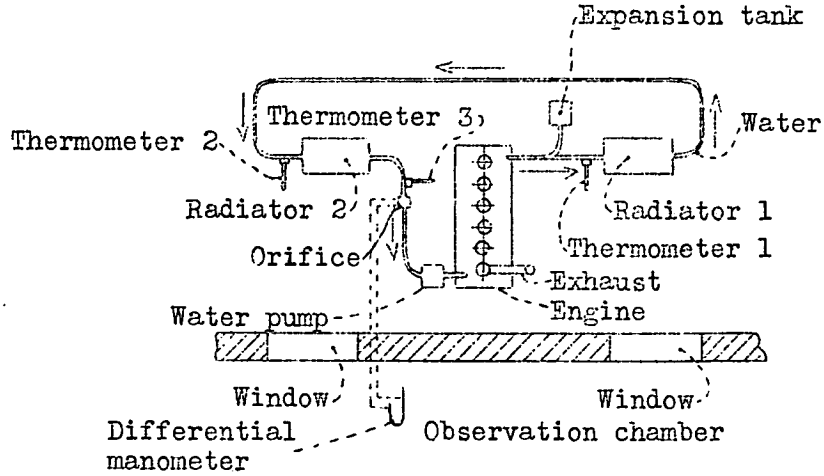


Fig.4 Arrangement on test stand.

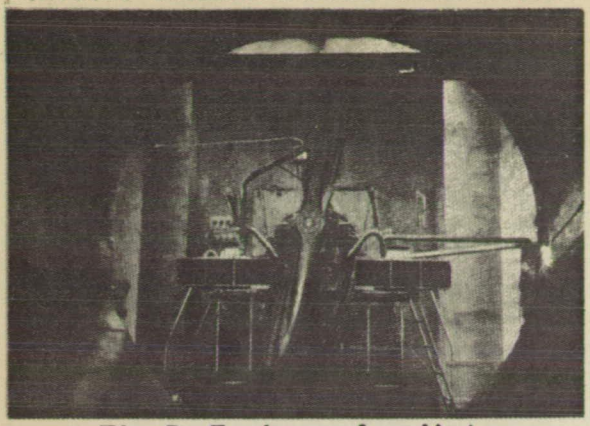


Fig.3 Engine and radiator on test stand.



Fig.9 Experimental airplane Arado SCI D 1241.

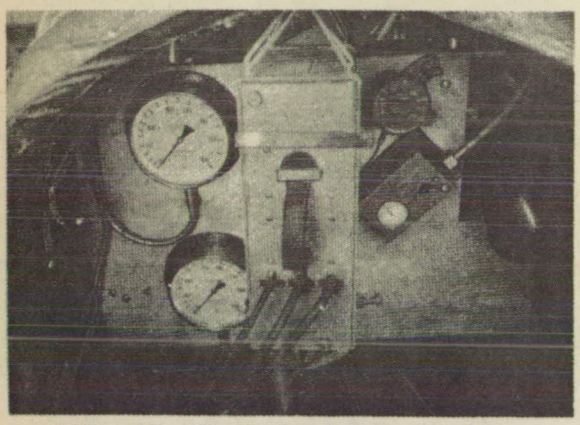


Fig.10 Test instruments in observer's cockpit.

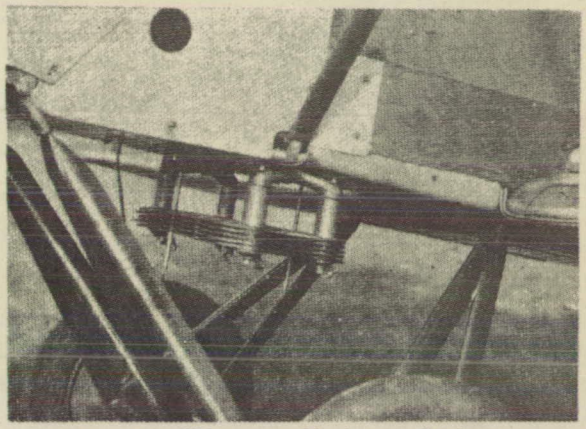


Fig.11 Five radiator plates farther from fuselage.

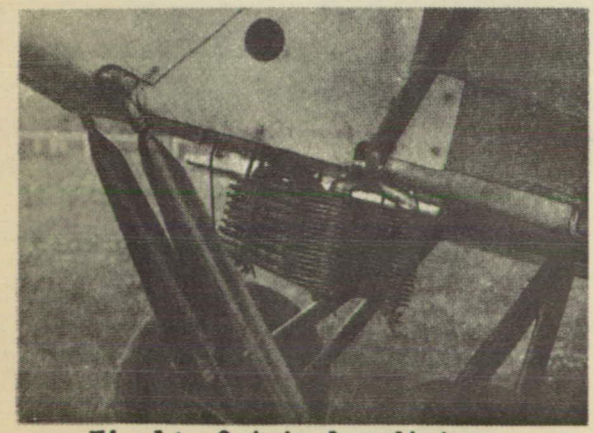


Fig.14 Original radiator with 19 plates.

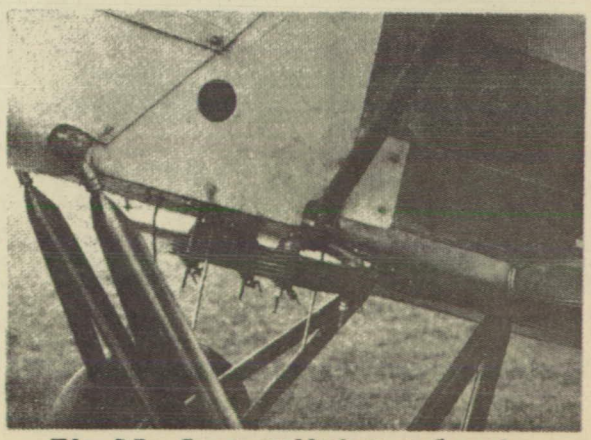


Fig.15 Same radiator reduced to 6 plates.

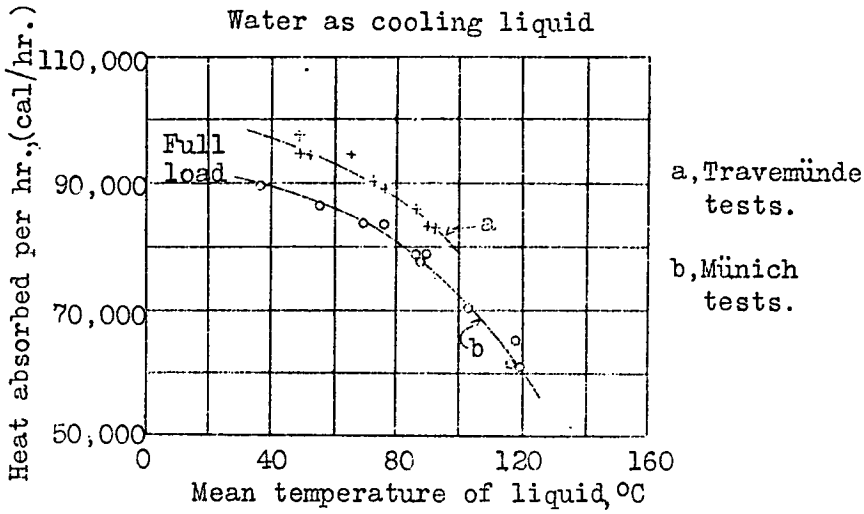


Fig.5 Hourly heat absorption against mean temperature of liquid.

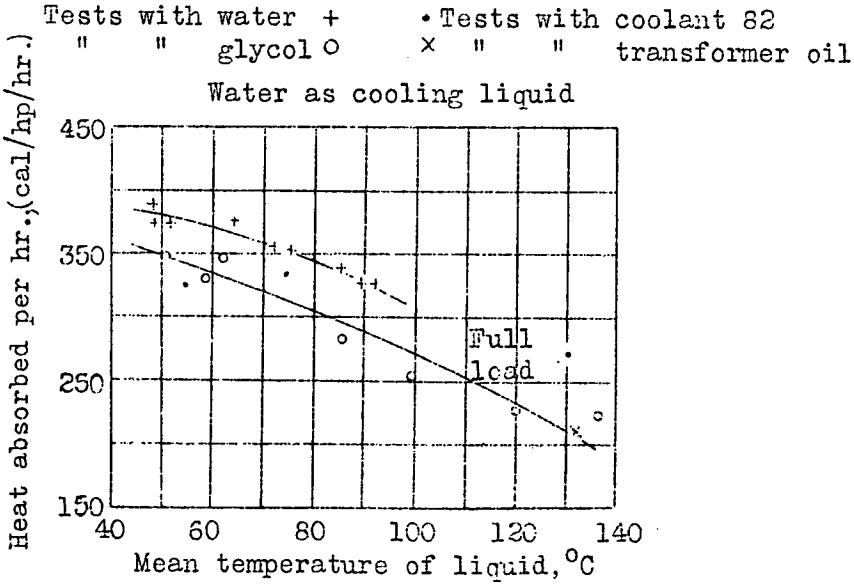


Fig.6 Heat absorption per hp/hr against mean temperature of liquid.

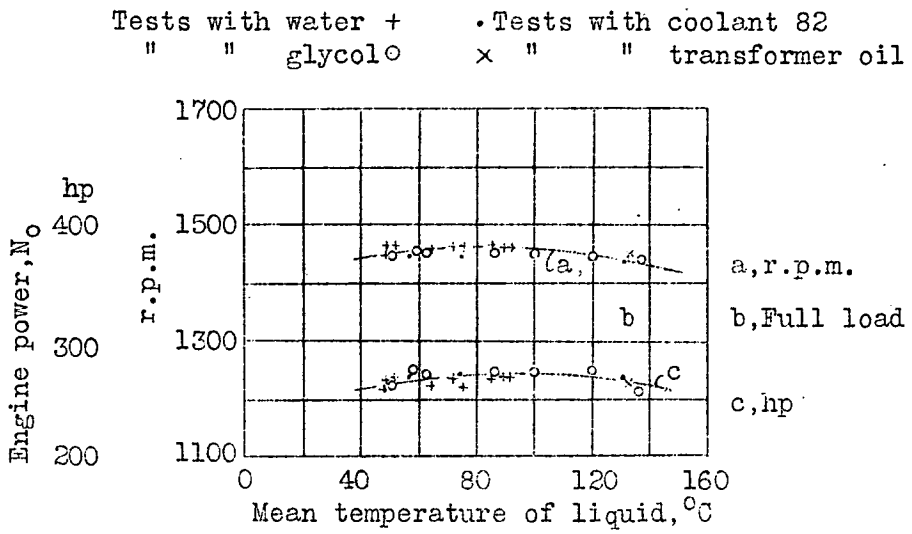


Fig.7 r.p.m. and N_o (in hp) against mean temperature of liquid.

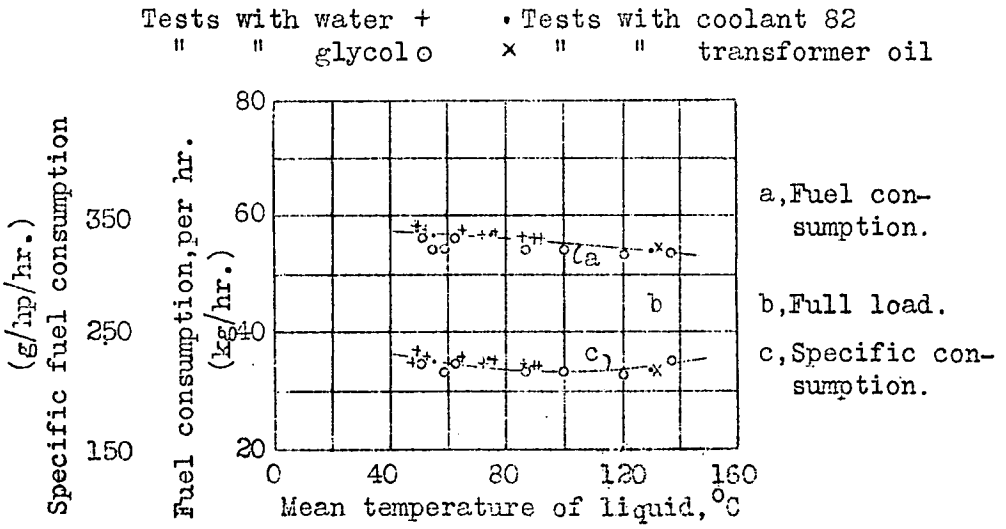
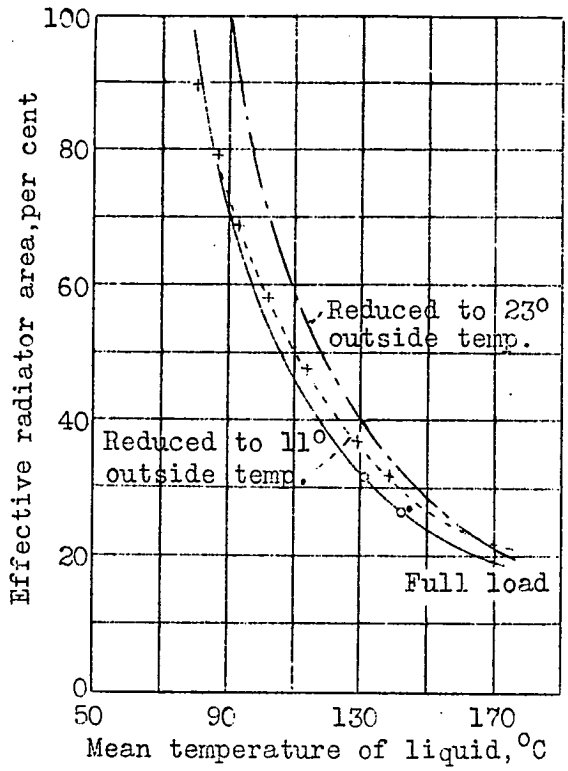


Fig.8 Hourly and specific fuel consumption vs mean temperature of liquid.



Cooling liquid, glycol. Arado SCI D 1241

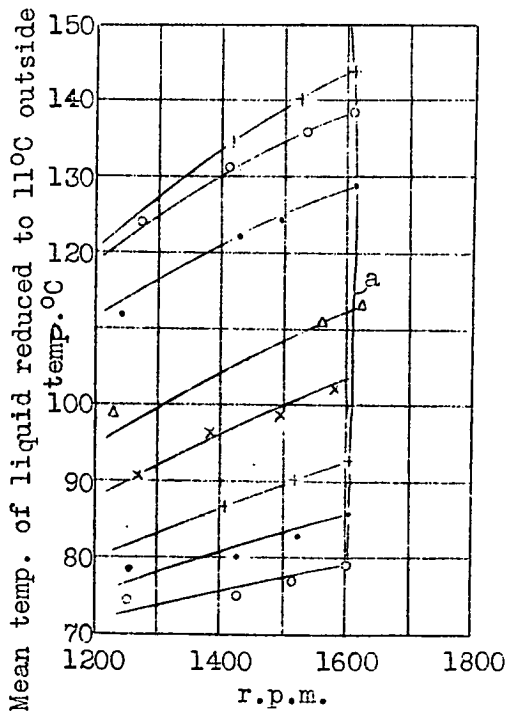
Original effective radiator area for water cooling=100%= 10.93 m^2=19 radiator plates.

• Radiator of new design

+ Removal of radiator plates from below.

o Improvement of radiator efficiency by lowering the plates.

Fig.12 Effective radiator area against mean temperature of liquid.



a; r.p.m. at full throttle.

Fig.13 Mean temperature of liquid reduced to 11°C outside temperature and plotted against engine r.p.m.